BEST MANAGEMENT PRACTICES EFFECTIVENESS TO REDUCE SEDIMENT TRANSPORT TO MORRO BAY

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ABSTRACT

BEST MANAGEMENT PRACTICES EFFECTIVENESS TO REDUCE SEDIMENT TRANSPORT TO MORRO BAY

Michael James Randall

The Morro Bay Watershed, which is located in San Luis Obispo County, California, covers more than 48,000 acres of land and discharges into Morro Bay through the Morro Bay National Estuary (MBNE). The Chorro Creek Subwatershed consists of approximately 30,000 acres of the overall watershed. The MBNE provides an ecosystem that supports a variety of wildlife from the common sea gull to the endangered sea otter. The estuary is also home to over 200 species of birds. The operational waterfront of the Morro Bay Harbor was and continues to be a strong supporter to the local economy of the City of Morro Bay. Numerous studies were conducted since the 1990s throughout the watershed to study the sedimentation of the estuary and bay and identified accelerated erosion and subsequent sedimentation as a major threat to sustainability of the bay. As a result, various Best Management Practices (BMPs) were implemented in the watershed to reduce sediment loading and transport to the bay. Localized evaluations of various BMPs have been performed to investigate effectiveness of individual BMPs. This paper consolidates this information and develops a comprehensive spatially distributed watershed simulation model (1) for detailed understanding of the erosion and sedimentation processes in the watershed; (2) to evaluate a watershed scale effectiveness of the conservation practices that were installed in the watershed; (3) to identify optimal BMP types and sites that may be used in the future to further reduce sedimentation of the bay at minimal cost; (4) to organize and document the various sources of data and studies that have been performed to date in the Chorro Creek subwatershed. Soil and Water Assessment Tool (SWAT) was used to develop the model and to evaluate the pre- and post-BMP implementation characteristics in the subwatershed. Combining the data and efforts of past BMP evaluations, land use, soil type, climate data, and streamflow data, statistical evaluations, and model sensitivity analysis will help build and calibrate a robust SWAT model that can be used to track BMP evaluation efforts, as well as other watershed management tasks. Through the evaluation of BMPs in the watershed, efforts can be made to implement the more successful BMPs in the watershed or in other similar watersheds. Sensitivity analysis was performed using a global sensitivity analysis method and streamflow and sediment yield was calibrated using the Shuffled Complex Evolution-University of Arizona.

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ArcGIS- Geographic Information System software package by Environmental Systems Research Institute

BMP- Best Management Practices

CCRWQCB- Central Coast Regional Water Quality Control Board

Erosion- process of removing or wearing down solid particles from a group of stable particles by an eroding media, such as water or air

GIS- Geographical Information System

MBNE- Morro Bay National Estuary

MUSLE- Modified Universal Soil Loss Equation

NEP- National Estuary Program

O&M- Operation and Maintenance

Sediment Transport- the process of particles moving, in this work through the use of water media.

Sedimentation- process of erosion, and is the process of solid particles being deposited from an eroding media to a group of stable particles.

SWAT- Soil and Water Assessment Tool 2005

SWRCB- California State Water Resources Control Board

USLE- Universal Soil Loss Equation

CHAPTER 1

INTRODUCTION

Sediment transport is a natural process that helps define the world's topography. A number of human activities have changed this natural process and communities are working to reestablish a sustainable management system to manage sediment transport. Water quality Best Management Practices (BMPs) were established to reduce and control sediment transport as part of a combined watershed management strategy. Watershed managers, water resource agencies, and water quality regulators are now coming together to balance needs in a collaborative community of practice. This group is comprised of individual technologists, managers, regulators, environmentalists, variety of landuse representatives, and the public. The BMPs this community of practice are developing and implementing, modify physical watershed characteristics such as channel geometry, bank erodibility, and channel roughness. If these BMPs are installed, operated, and maintained properly, they can limit the availability of sediment for transport or capture sediment that is being transported from upstream in the watershed.

The installation costs, as well as long term operation and maintenance (O&M) of BMPs, are driving factors in the decision making process regarding BMP implementation. The need for BMP evaluation prior to large scale investment is often beneficial. Developing an optimized and sustainable sediment management plan can be difficult due to the uncertainty of BMP performance. There are many factors that effect typical BMP performance and these factors vary greatly form location to location. It is impossible to develop a specific set of BMPs that will be the best solution for all watersheds. Instead, it is critical to evaluate the existing conditions within the target watershed and select BMPs that will be effective at achieving the preferred sediment transport yield within the basin and have reasonable long term O&M investment.

BMPs need to be evaluated on a case by case basis. By collecting detailed watershed characteristics and evaluating the aggregate system they define, watershed managers can determine which BMPs will be most effective in managing sediment transport.

Streams naturally erode the stream bed and banks as the water flows through the channel. Overland flow in the form of runoff also carries sediment from hard surfaces within the watershed. Sediment yield is the total measured amount of eroded sediment transported from upstream and from overland sources to the measuring or monitoring point. The Central Coast Regional Water Quality Control Board (CCRWQCB) classifies contaminant sources into two types, point source, and non-point source. Point sources are defined long-term or short term discharge sources which have a fix point of contaminate discharge to the receiving water body. Non-point source discharges are contaminant discharges which do not have a fix point of discharge. Sediment loading, the amount of sediment that is released from the flowing river or creek to the downstream receiving water body, is predominantly from non-point source discharges along the stream or channel (CCRWQCB 2002). This has caused regulators and dischargers to develop and employ BMPs to reduce this contamination.

Point source discharges have been regulated to meet increasing pollutant regulations since the introduction of the Clean Water Act in 1972. As dischargers and regulators work to reduce the environmental impact of these point source discharges, the impacts of non-point source discharges become more apparent. Non-point source loading and contamination is becoming more closely tracked as an unmitigated source of contamination (CCRWQCB 2002). There are a variety of types of sediment reducing BMPs, and each type has numerous variations. The standard BMP types comprise of grazing practices, stream bank stabilization, irrigation practices, sediment capture, and channel geometry practices.

Computer models are used to evaluate the effectiveness of BMPs, assess BMP alternatives, and evaluate location selection. Computer models can estimate the effectiveness of basin-wide BMP implementation based on the effectiveness of smaller scale case studies. These estimates can help guide decisions on where BMPs should be implemented and how effective they might be when implemented. As more data is collected the model can be further calibrated to provide more accurate results. Conducting full scale studies with in the basin are expensive and time consuming. Computer models are capable of simulating BMPs for relatively low cost and without investing the time required to install and monitor BMPs in the field. For these reasons computer models are being more widely used to aid in the direction of BMP implantation projects. A variety of computer models are available that analyze stream hydraulics and hydrology, which can be used to model sediment water quality BMPs. These models are starting to incorporate finer modeling modules and look at a wider range of potential watershed characteristics.

This study consolidates the information from the various BMPs that were implemented in the watershed into a global sediment model approach. The implemented

BMPs were modeled using a geospatially distributed computer model that allows for the input of a wide variety of input parameters. The BMP evaluation can benefit greatly from the increasing amount of available Geographical Information System (GIS) data. The two goals of this evaluation are to organize and document the various sources of data and analysis that have been performed to date in the Chorro Creek Subwatershed and to present a global evaluation of the effectiveness of the BMPs that have been implemented in this watershed using Soil and Water Assessment Tool 2005 (SWAT) in order to simulate the pre- and post-BMP implementation characteristics evaluated in the Chorro Creek Subwatershed. Combining the data and efforts of past BMP evaluations, land use, soil type, rainfall, and streamflow data, past statistical evaluations, and model sensitivity analysis helped build and calibrate a robust SWAT model. This model can be used to track BMP evaluation efforts, as well as other watershed management tasks. Through the evaluation of BMPs in the Morro Bay Watershed, efforts can be made to implement the more successful BMPs in the watershed. SWAT can be used as a prediction model to estimate the effectiveness of BMP implementation and aid in the selection of appropriate BMPs for the specific watershed.

CHAPTER 2

BACKGROUND

The Morro Bay Watershed, which is located in San Luis Obispo County, California, covers more than 48,000 acres of land and discharges into Morro Bay through the Morro Bay National Estuary (MBNE). A vicinity map of the watershed is shown in Figure 2.1. Figure 2.2 shows the boundary of the Morro Bay Watershed, and Figure 2.3 shows the boundary of the Chorro Creek subwatershed. The MBNE provides an ecosystem that supports a variety of plants and animals, from the common sea gull to the endangered sea otter. The estuary is also home to over 200 species of birds. The operational waterfront of the Morro Bay Harbor was and continues to be a strong supporter to the local economy of the City of Morro Bay.

One of the principal contaminates of concern in this watershed is sediment due to its effects on wildlife both in the bay and in the tributary creeks. Human activity has altered the watershed over time. It is important to understand whether these activities are negatively affecting the watershed and, if so, to what extent. There are many agencies and organizations that are working to evaluate and improve sediment conditions in the watershed. Currently, sediment deposits are removed from the bay approximately every two years by the United States Army Corps of Engineers (Crops). This activity is necessary to keep the bay navigable for vessels and sustain the habitat that many animals depend on. Morro Bay is designated as a habitat area for eelgrass, which grows on the bottom of the bay. The dredging activity potentially threatens the eelgrass and animals in the bay. Depending on the effectiveness and environmental impact of sediment transport reduction best management practices (BMPs) in the tributary waterways, dredging activities in the bay could be reduced. If large amounts of sediment can be retained or captured in the tributary creeks, sediment loading to the bay would be minimized.

Figure 2.1: Study Area Location Map

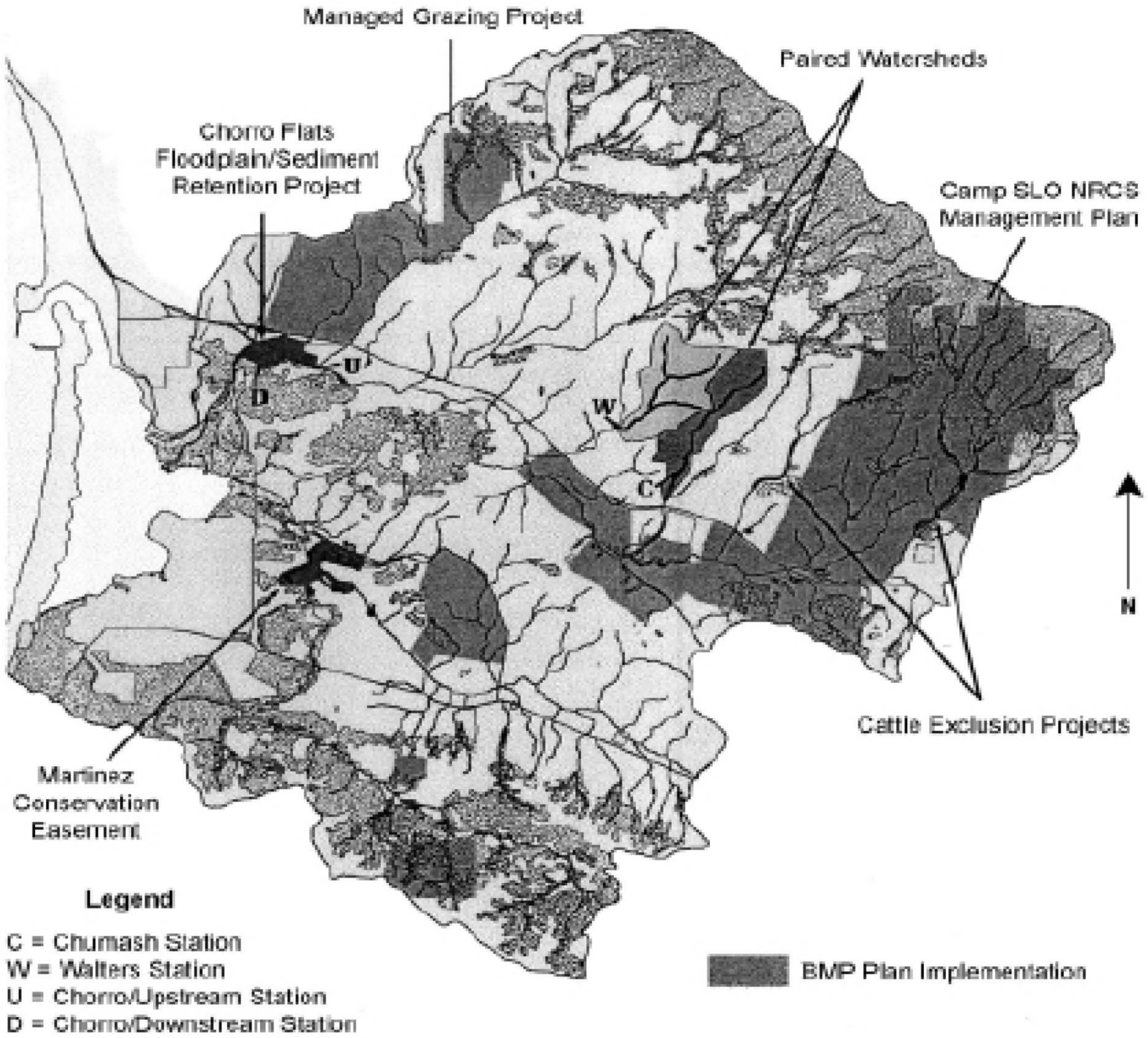

Figure 2.2: Morro Bay Watershed Map of Major BMPs. (Source: CCRWQCB, 2002)

Numerous studies have been conducted since the 1990s throughout the watershed to study the sedimentation of the estuary and bay. These studies primarily focused on the evaluation of various BMPs to reduce sediment loading and transport through the watershed. Localized evaluations of various BMPs were performed in studies to evaluate localized effectiveness of BMPs. The CCRWQCB and the California Polytechnic University (Cal Poly) conducted a best management effectiveness study, known as the paired watershed study, from 1992 to 2002 on Walters Creek and Chumash Creek in the North East portion of the Chorro Creek Watershed, shown in Figure 2.3.

Walters Creek had no BMPs installed along its reach and was used as a control watershed, while Chumash Creek had various BMPs installed, including grazing management, stream bank stabilization, cattle exclusion fencing projects and planting native riparian trees along stream banks. Observation was conducted over a 10 year study period to determine the effectiveness of BMPs and to calibrate and validate sediment yield. Sediment yield, streamflow, nitrate concentrations, and other water quality parameters were collected during the rainy season for both creeks. This data was reviewed and analyzed to determine the effectiveness of the BMPs installed on Chumash Creek, which was accomplished by evaluating the difference in sediment yield between the pre- and post-BMP implementation. Walters Creek data was used to normalize the data and remove any fluctuations in sediment yield due to events other than BMP installation.

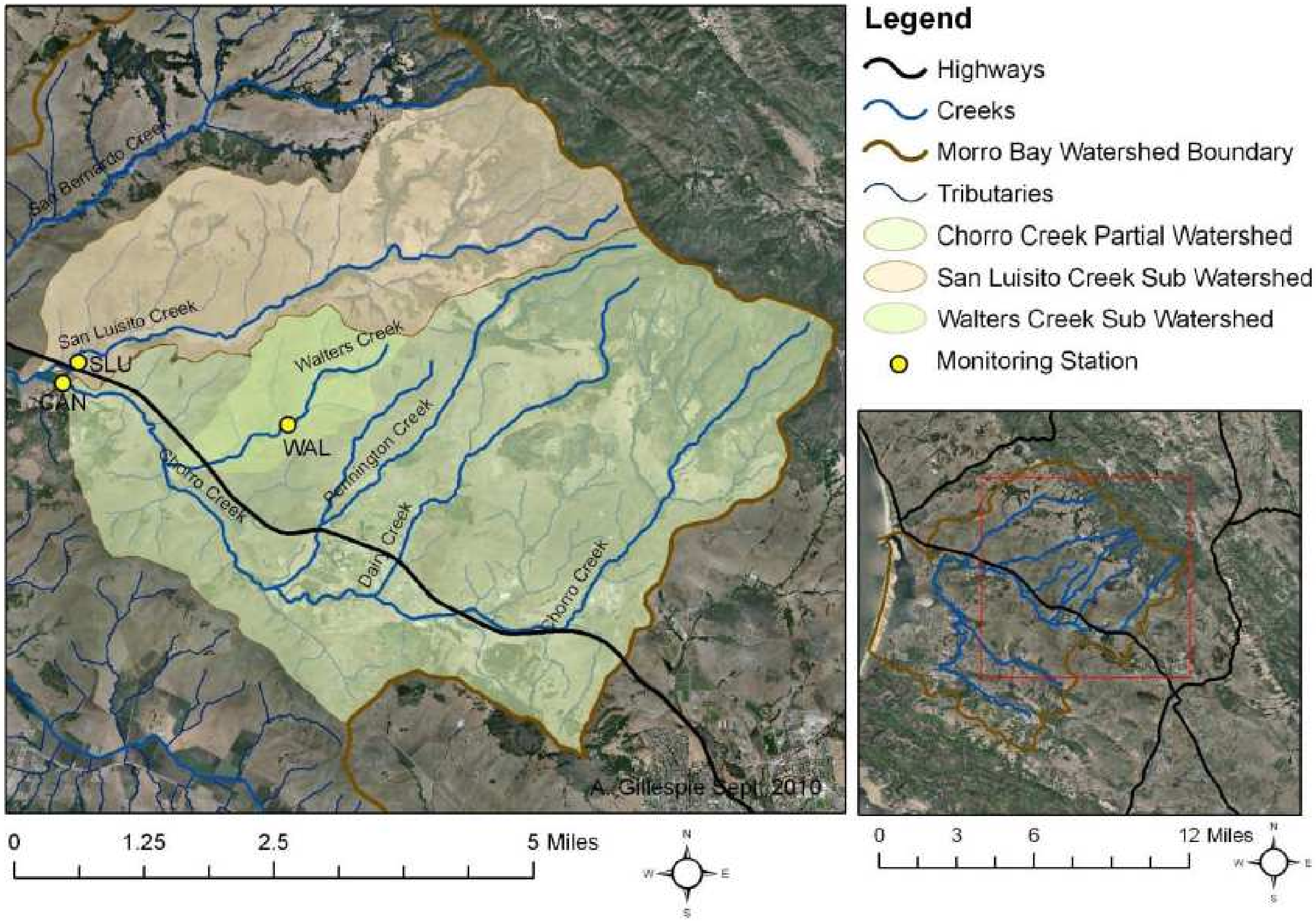

Figure 2.3: Chorro Watershed Study Area. (Source: MBNEP, 2010)

The CCRWQCB, which is tasked with regulating new and existing sediment discharges in the watershed, conducted a study on the "Morro Bay Total Maximum Daily Load (TMDL) for Sediment (including Chorro Creek, Los Osos Creek and the Morro Bay Estuary)." In the study, the CCRWQCB evaluated many of the contributing factors of sediment to Morro Bay, including flushing action, stream sediment transport, background erosion in the bay, and other contributing factors. The study attributes most of the sedimentation of the bay to "creek-born" sediment transport. The study used data collected by Tetra Tech as part of the paired watershed study and Chorro and Los Osos Creek Monitoring Programs. The CCRWQCB identified that Chorro Creek averages 19,200 tons/year of sediment transport to the bay.

The study evaluated the various beneficial water users in the basin. The report outlined the various types of users and describes the impacts that sedimentation has had on the users. These users include cities, communities, farmers, recreational farmers, and environmental stakeholders. The study is used to determine the impacts of sedimentation and give a baseline for sedimentation in the region. The report sets future TMDL targets with the primary goal of reducing sediment loading in the basin to reduce the impacts on users in the basin. The TMDL report outlines impacts and discharge types to support regulation findings and permit conditions on potential dischargers.

> Over time, all estuaries eventually fill with sediment due to the natural processes of erosion and sedimentation. However, the concern with Morro Bay is that these natural processes have been accelerated due to anthropogenic watershed disturbances. Studies conducted by various authors over the past 25 years have concluded that the rate of sedimentation to Morro Bay has rapidly increased.

> These studies have provided either estimates of sediment loadings to the Bay from the creeks emptying into the Bay, or estimates of sediment accumulations within the Bay. (CCRWQCB 2002)

Several BMPs have been implemented in the Morro Bay Watershed to help reduce sediment transport. These implemented BMPs include sediment harvesting, exclusion fencing, land conservation/retirement from farming, and bank stabilization (CCRWQCB 2002).

The Morro Bay National Estuary Program (MBNEP) conducts routine monitoring of sediment and submits an annual Sediment Monitoring Report for the Morro Bay Watershed to the CCRWQCB. The MBNEP has groups of volunteers that collect the data throughout the year. The annual report summarizes the year's monitoring, assesses the state of the watershed, and evaluates the effectiveness of installed BMPs.

CHAPTER 3

BMPs COMMONLY USED TO CONTROL SEDIMENT YIELD

There are two main components that effect sediment transport. These two components are erosion and sedimentation. Erosion is the process of removing or wearing down solid particles from a group of stable particles by an eroding media, such as water or air. Sedimentation is the reverse process of erosion, and is the process of solid particles being deposited from an eroding media to a group of stable particles. The rates of these two processes determine the amount of sediment available for sediment transport. When the rate of erosion increases, the amount of available sediment increases and the amount of sediment transport increases. If the rate of sedimentation decreases, less sediment is removed from the flow stream resulting in increased sediment available for sediment transport.

There are many factors that effect erosion and sedimentation. Typical factors that effect erosion in natural river environments include:

- Erodibility: the measure of how easily erodible a material is.
- Flow Velocity
- Volumetric Flow Rate
- Water Surface Elevation
- Channel Slope

Typical factors that effect sedimentation in natural river environments include:

- Volumetric Flow Rate
- Particle Size
- Flow Velocity
- Channel Geometry

The above erosion and sedimentation factors are represented in SWAT and used in model computations to represent the amount of erosion and sedimentation occurring in the modeled system. The balance of the rate of erosion and the rate of sedimentation at a location in the river determines the amount of sediment added or removed in a channel section. This balance is determined from comparing the amount of sediment deposited along the channel section and the amount of sediment added to the channel flow through erosion along the same channel section. Sediment yield increases if the rate of sedimentation is greater than the rate of erosion. The opposite relationship is also valid when the rate of sedimentation is less than the rate of erosion sediment yield decreases.

The BMPs evaluated in this case study evaluation reduce sediment transport by either increasing sedimentation in the stream channel, or decreasing erosion along the river reach. These changes can benefit the receiving water body by reducing the amount of sediment that is discharged from the tributary flow channel.

Chorro Flats

Sediment Harvesting was conducted in the Chorro Flats located near the discharge mouth of Chorro Creek prior to entering the oceanic ecosystem in Morro Bay. Sediment harvesting reduces the amount of available sediment for erosion by removing easily eroded sediment from the creek channel and allowing available storage and cross sectional area to assist in sedimentation.

Exclusion Fencing

Exclusion fencing is a BMP that aims to reduce erosion caused by grazing cattle by limiting or completely preventing livestock from entering the channel and erodible bank limits. Bracmort et al. (2006) found that measurable creek-born sediment originates from cattle and other livestock releasing and generating loose sediment on the channel slopes and floor during grazing and migrating along the creek channel. If livestock crossings is prohibited or diverted to designated access routes, sediment erosion in the channel can be reduced.

Bracmort et al.(2006) estimated that sediment transport in watersheds can be reduced by up to 50 percent during peak flow events through the implementation of exclusion fencing on agricultural grazing lands. This analysis will estimate the anticipated reduction in sediment transport from the implementation of exclusion fencing by modifying land use and the channel bank erodibility factor, which is described in more detail in Chapter 7.

Stream Bank Stabilization

Stream bank stabilization is a frequently used BMP in watershed management and sediment yield reduction projects. It reduces the amount of available soil for erosion by replacing a material that has high erodibility (typically exiting exposed soil) with a material with a lower erodibility (typically rip rap, rock, or concrete). This slope protection also helps keep the channel geometry fixed by reducing expansion of the channel. Channel expansion can result in lower stream flow velocities increasing the rate of sedimentation. Stream bank stabilization helps protect the existing rate of sedimentation or a designed rate of sedimentation to create a stable sediment yield by helping to set a fixed average flow velocity and volumetric flow rate relationship.

Conservation Crop Rotation

Conservation Crop rotation is an agricultural BMP which balances external needs from different crops over the watershed or managed agricultural land. Sediment generated by crop irrigation runoff can be reduced by rotating crop types over the available landuse area. In some cases conservation crop rotation can include time periods of rest or fallowing when the field is set aside and not planted for a crop rotation. Crop rotation has the greatest effect on nitrogen and phosphorus levels in the watershed but also changes irrigation patterns depending on the managed crop rotation (Arabi et al.2007). Periodic land fallowing reduces field runoff and reduces erosion associated with field irrigation runoff.

CHAPTER 4

THE WATERSHED SIMULATION MODEL

Soil and Water Assessment Tool (SWAT), which was developed by the USDA's Blacklands Research Center, was used in this study. SWAT is a continuous-time, spatially distributed simulator developed to assist Water Resource Managers in predicting impacts of land management practices regarding water, sediment, and agricultural chemical yields. The model is well suited for large, complex watersheds with varying soils, land use, and management conditions over long periods of time (Nietsch, et al., 2005; Arnold et al., 1999). SWAT uses watershed specific information like weather, soil, topography, vegetation, and land use practices to simulate watershed processes, such as surface runoff, subsurface flow, streamflow, sediment transport, sediment yield, and nutrient loading, among others. The model is commonly used on a daily time scale. The model spatially divides the watershed into smaller subwatersheds or subbasins based on topography. These subbasins represent small units of the overall watershed that can be used to approximate the behavior of the overall watershed. The subwatersheds are divided further by the model into hydrologic response units (HRUs), which are assigned homogeneous soil type, land use, weather, and slope. This categorization allows the model to create homogeneous units that can be modeled to predict how the heterogeneous properties of the watershed will respond to changes in input parameters, such as rainfall, land use changes, and topography.

As a distributed model, a major concern that may arise with the practicality of SWAT may be its numerous and varied data requirements. For the U.S., the required data is commonly available in high enough resolution from government agencies that a model can be created relatively quickly. For watersheds that lack weather stations, the model has the capability to generate synthetic monthly weather data using a stochastic weather simulator. The ability of SWAT to integrate with the ongoing expansion of ArcGIS data helps alleviate difficulties locating, formatting, and importing data. All these comprehensive features make SWAT ideal for use in integrative watershed management systems. Figure 4.1 is a view of the constructed spatially distributed model developed through this study.

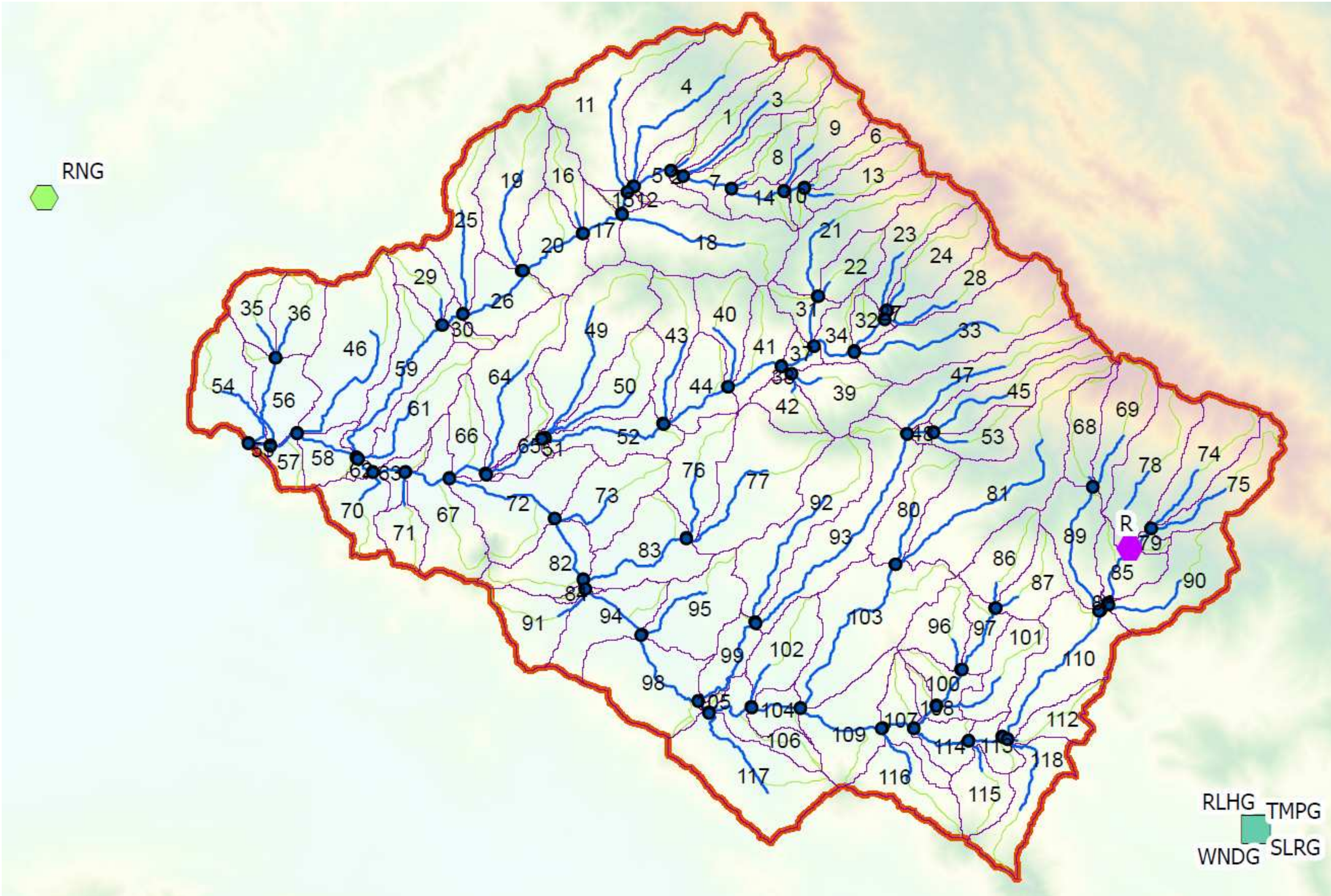

Figure 4.1: ArcSWAT Model Map

Model Selection

SWAT incorporates many characteristics and relationships into its watershed modeling and is applied to watershed studies to make predictions of future watershed characteristics with and without changes in the watershed. SWAT is capable of modeling several watershed parameters to determine the effects on watershed performance such as sediment transport. SWAT was primarily chosen for this analysis due to is spatially distributed modeling method which is able to represent watershed properties spatially through the watershed and factor in heterogeneous changes in a variety of watershed characteristics described later in this chapter.

SWAT is used to evaluate water quality benefits of agricultural conservation practices and watershed BMPs. SWAT has been used to analyze sediment transport and the effect of BMP implementation in a number of watershed studies. One such study was conducted in Thailand on the Lam Sonthi River Watershed (Phomcha, et al 2011). SWAT was used to build and calibrate distributed hydraulic model of the study watershed to assess the process of sedimentation. Thailand has mountainous terrain with large amounts of rainfall and high rainfall intensity from its tropical climate. The model is being used to predict erosion processes to aid in watershed management and demonstrate the value of modeling watersheds with SWAT (Phomcha, et al 2011)

Richnavsky constructed a simulation model of the Ostravice River Basin in the north-eastern part of the Czech Republic using SWAT to model sediment transport in the watershed. The model was used to determine where the highest sediment routing and sediment concentrations are occurring to determine what areas should be focused on in future studies. The implementation of the model was used to highlight the importance of tracking sediment data in the watershed and the value of distributed hydraulic models (Richnavsky, et al 2010).

SWAT's ability to represent a wide variety of input parameters spatially distributed over a geospatial study area allows for a more detailed watershed model than other modeling packages. The level of detail able to be simulated in the model is limited by the amount of data collected and the speed of calculation not the models capacity to store data. As additional data is collected SWAT is able to easily incorporate that data into the model structure. SWAT's sensitivity analysis function, which will be described in future detail in Chapter 5: Sensitivity Analysis and Calibration, can be used to determine what data is most valuable to improve the accuracy of the data by determining how sensitive the desired output parameter is to the potential input parameters that can be monitored in the watershed. See Chapter 5 for more details on sensitivity analysis and calibration.

Models which incorporate geospatial data are becoming more widely used to the increased use of GIS software and data files. As professionals become more familiar with GIS data, modelers will have larger and more detailed data sets to incorporate into models, such as SWAT. For these reasons SWAT has become a standard tool of practice in the modeling community as described by Arabi et al. (2007), and is strengthening the use of computer models in watershed management as well as qualitative and quantitative watershed studies.

This study incorporates the existing and ongoing efforts of the NEP and RWQCB. These organizations are working to track, monitor, and regulate sediment loading in the Chorro Creek Watershed. Through the development of this model a basin wide vision of the watershed impacts due to sediment has been developed. The model also allows for production simulations to be conducted outside of the BMPs covered in this analysis. The implemented BMPs in this analysis were modeled to help predict the benefits of various BMPs that have been or are practical to incorporate within the watershed.

Runoff

Sediment loading is highly dependent on precipitation within the watershed. Excess water from precipitation, that is not stored within depressions in the ground or infiltrated into the ground, is classified as runoff. This overland flow caries nutrients and sediment as it travels towards the stream channel. Runoff increases stream flow and must be estimated accurately in order to model streamflow and sediment transport within in a watershed. SWAT uses the SCS curve number procedure (SCS, 1972) and the Green & Ampt infiltration method (1911) (Neitsch, et al. 2005) to estimate runoff during simulated precipitation events within the watershed model.

"The SCS Runoff equation is an empirical model that came into common use in the 1950s. It was the product of more than 20 years of studies involving rainfall-runoff relationships from small rural watersheds across the U.S. The model was developed to provide a consistent basis for estimating the amounts of runoff under varying land use and soil types" (Rallison and Miller, 1981).

The SCS curve number equation is (SCS 1972):

$$Q_{surf} = \frac{\left(R_{day} - I_a\right)^2}{\left(R_{day} - I_a + S\right)} \qquad 2:1.1.1$$

- Q_{surf} is the accumulated runoff or rainfall excess (mm H_2O)

- R_{day} is the rainfall depth for the day (mm H_2O)
- I_a is the initial abstraction which includes surface storage, interception and infiltration prior to runoff (mm H_2O)
- S is the retention parameter (mm H_2O). (Neitsch, et al. 2005)

The retention parameter varies spatially due to changes in soils, land use, management and slope and temporally due to changes in soil water content. The retention parameter is defined as:

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \qquad 2:1.1.2$$

- CN is the curve number for the day.

The initial abstractions, I_a, is commonly approximated as 0.2S. The surface flow equation becomes:

$$Q_{surf} = \frac{\left(R_{day} - 0.2S\right)^2}{\left(R_{day} + 0.8S\right)} \qquad 2:1.1.3$$

Runoff will only occur when $R_{day} > I_a$." (Neitsch, et al. 2005)

SWAT uses a conversion table to estimate the SCS Curve number for each soil type input into the model. This curve number factors in soil type and land use as well as soil water conditions. This dynamic selection of curve number provides a more accurate model than other fixed curve number numerical methods and models.

Streamflow Routing

SWAT uses the Muskingum routing method to route flow and sediment through the stream network of the watershed. The model incorporates losses in flow from factors such as evaporations and infiltration. The model also has the ability to factor in point sources of flow additions or reductions such as surface water pumping or point source water discharges. SWAT provides the modeler with tools to model flow impacts within the channel throughout the watershed.

The Muskingum method is used to develop the flowing routing equation used by SWAT:

$$q_{out,2} = C_1 \cdot q_{in,2} + C_2 \cdot q_{in,1} + C_3 \cdot q_{out,1} \qquad 7{:}1.4.3$$

- $q_{in,1}$ = inflow rate at the beginning of the time step ($m^3/2$)
- $q_{in,2}$ = inflow rate at the end of the time step
- $q_{out,1}$ = outflow rate at the beginning of the time step
- $q_{out,2}$ = outflow rate at the end of the time step

SWAT models two types of channels, both main channel and tributary channels within a subbasin. Tributary channels are subordinate flow channels that contribute flow to the main channel. These tributary channels convey nutrients and sediment to the main channel and contribute to the overall nutrient and sediment load within the basin. Therefore it is critical to incorporate these sediment calibrations into a basin wide sediment transport model analysis. By incorporating the detailed characteristics of the tributary channels instead of simply attributing the tributary sediment load at nodes along the main channel, SWAT is able to provide a better fit by having finer adjustment during calibration. The model provides a more realistic representation of the watershed and contains modeling parameters that are ignored by models that do not account for tributary stream parameters.

Sediment Routing

SWAT routes sediment by simulating both sediment deposition and degradation, Williams (1980) and Bagnold (1977) determined that channel degradation was a function of channel slope and flow depth or channel water velocity. SWAT sets the maximum sediment transport in a reach using William's and Bagnold's definition of stream power based on the channel peak channel velocity (Neitsch, et al. 2005). Erosion and Sediment yield from overland flow is simulated using the modified universal soil loss equation (MUSLE) which simulates sediment deposition proportionally to channel velocity.

MUSLE differs from the original universal soil loss equation (USLE) by replacing the energy factor with a runoff factor. SWAT states that this change "improves the sediment yield prediction, eliminates the need for delivery ratios, and allows the equation to be applied to individual storm events." (Neitsch, et al. 2005). Williams developed the MULSE because it was determined that runoff is a function of antecedent moisture condition as well as rainfall energy. The MUSLE incorporates both of these factors by using both a delivery ratio and a runoff factor to estimate erosion energy.

The MUSLE is defined as:

$$sed = 11.8 \cdot \left(Q_{surf} \cdot q_{peak} \cdot area_{hru}\right)^{0.56} \cdot K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE} \cdot CFRG \qquad 4:1.1.1$$

- *sed* is the sediment yield on a given day (metric tons),
- Q_{surf} is the surface runoff volume (mm H_2O/ha),
- q_{peak} is the peak runoff rate (m^3/s), $area_{hru}$ is the area of the HRU (ha),
- K_{USLE} is the USLE soil erodibility factor (0.013 metric ton m^2 hr/m^3-metric ton cm)).
- C_{USLE} is the USLE cover and management factor,

- P_{USLE} is the USLE support practice factor, LS_{USLE} is the USLE topographic factor
- *CFRG is the course fragment factor. (*Neitsch, et al. *2005)*

CHAPTER 5

WATERSHED DATA

The Chorro Creek Subwatershed was mapped using a high resolution digital elevation map (DEM) to determine the high points that border the watershed. Once the boundaries of the watershed were determined, soil type, land use, precipitation, evapotranspiration, temperature, and other weather data for the watershed were collected from various sources. The data collected was integrated into the SWAT model.

Topography

Elevation data was collected for the watershed from the United States Geological Survey (USGS). A DEM of the basin was obtained with a 10m by 10m resolution. This data was used to help generate the boundaries of the watershed, stream location, and slope parameters in the watershed.

Soil Data

Soil type information was obtained from the National Recourses Conservation Service. This data was cross checked with USGS soil data. Soil type is used by SWAT to develop HRU parameters, such as curve number.

Landuse Data

The county's land use data was used to compile land use types for the model. SWAT uses land use to calculate HRU parameters and determine hydrologic responses to rainfall. Land use was altered to simulate installation of BMPs in the watershed.

Climate and Rainfall Data

Daily rainfall data in the urban community of Morro Bay directly adjacent to the Chorro Subwatershed was used to estimate historic rainfall information for the basin. The location of this data is a possible source of uncertainty in the calibration of the model.

Streamflow Data

Streamflow data was collected for the Canet Road stream gage located in the basin. This gage is monitored by the County of San Luis Obispo Department of Public Works. The data at the Canet stream gage location was converted from stage readings to streamflow using a rating curve obtained from streamflow monitoring conducted by the MBNEP and the City of Morro Bay. Flow data was also obtained for Walters and Chumash creeks from the Paired Watershed Study data.

Sediment Data

Sediment data was compiled from the existing data collection efforts in the basin. The MBNEP and NRCS have conducted numerous sediment studies. This data is not currently monitored continuously and is another potential source of uncertainty in the calibration step of the SWAT model.

Initial Model Parameters

The characteristics of the 118 HRUs or subwatersheds in this model analysis are shown in Table 4.1 the Appendix. Additional model input parameters are shown in Table 4.2 of the Appendix.

The values presented in Table 4.1 are the initial model parameters prior to modeling BMP implementation in the watershed. The parameters in Table 4.2 are additional model parameters set initially by SWAT and updated during model simulation. The BMP analysis required modifications to HRU parameters to represent the implementation of some of the BMPs. These modifications are described in detail in Chapter 7: Results and Discussion.

CHAPTER 6

SENSITIVITY ANALYSIS AND CALIBRATION

In order to ensure that the model watershed is representative of the Chorro Creek Watershed, sensitivity analysis and calibration must be conducted. Sensitivity analysis is used in modeling to determine which input parameters are most sensitive to the model results of interest. In this model evaluation of the variability of streamflow and sediment yield are the outputs being evaluated which should be calibrated. The sensitivity analysis provides a ranking of input parameters that have the greatest impact on the streamflow and sediment yield output. The highest ranked parameters should be used to perform the model calibration. The sensitivity analysis method used in this evaluation is known as One-at-a-time Latin hybercube (OAT) (Griensven, et al. 2006). This method evaluates changes in the target output parameters, such as streamflow and sediment yield, by altering the input parameters one at a time over there accepted range. SWAT conducts numerous model simulation runs, changing each input value one at a time. The computer model can evaluate the relationship between the model outputs versus changes in the model input parameters. Input parameters that are found to not have a significant impact on the output can be ignored during the calibration step, because these inputs have been determined to not have an effect on the outputs of interest. Model input parameters that rank high in the sensitivity analysis have the greatest influence on the model outputs and thus, should be selected as parameters for calibration.

Calibration refers to the process of identifying the “best” set of model parameters to match the simulated outputs and observed data. Calibration consists of manually or automatically adjusting model parameters to match the models simulation output to a known set of observation data. Parameters are typically altered manually by a trial-and-error process to meet a desired relationship between the model simulation output and the observed data. Calibration can also be conducted automatically using a defined optimization method. A desired threshold or acceptable error between the model simulation output and the observed data can be set along with bounding conditions for each significant parameter identified during sensitivity analysis. Automatic calibration is objective and more robust than manual calibration due to the number of model iterations automatic calibration is able to carry out. The computer model is able to quickly change input parameters and monitor model simulation output without stooping to receive human input commands. Automatic calibration is less time consuming and less subjective than typical manual calibration. It also removes a large amount of modeler judgment in regards to knowledge of the watershed by setting objective optimization criteria versus the more subjective criteria used in the manual trial-and-error calibration technique.

SWAT uses the Shuffled Complex Evolution (SCE-UA) automatic calibration algorithm from Duan, et al. (1992) to adjust input parameters and compare simulated and observed outputs. This method uses optimization function to determine optimal parameter values that closely match model simulation output and observation data.

The last phase of model calibration is the validation or verification step. During model validation the final parameter values for the parameters adjusted during calibration are used and the model is run for a different time series with known observation data other than that used during calibration. After running this second time series the model simulation output is compared to the observation data for the time series. This comparison allows the modeler to determine the performance of the model outside of the calibrated time series and to analyze the model's ability to predict accurate output. If the model picked the "best" set of model parameters to match the simulated outputs and observed data, then the model output should be as close as possible to the observed data for the time series modeled for validation. The closer the model simulation output is to the observed data the more robust the model.

Sensitivity Analysis

A sensitivity analysis was conducted to determine which of the unknown variables have the largest effect on the sediment yield and streamflow in the model. The results from the sensitivity analysis indicated which variables were the most influential variables. The most influential variables were selected as variables in the calibration stage of the modeling effort. Sensitivity analysis was performed using an OAT sensitivity analysis method and streamflow and sediment yield were calibrated using Shuffled Complex Evolution-University of Arizona (SCE-UA).

The results from the sensitivity analysis are shown below in Table 6.1. The five highest ranked parameters have the largest effect on sediment yield and streamflow.

Table 6.1: Streamflow Sensitivity Analysis Results

Parameter	Description	Rank	Used for Calibration	Mean
Cn2	Curve Number	1	Streamflow	0.696
Alpha_Bf	Base Flow Recession	2	Streamflow	0.323
Esco	Soil Evaporation Compensation Factor	3	Streamflow	0.297
Sol_Z	Soil Depth	4	NA[1]	0.244
Sol_Awc	Available Soil Water Capacity	5	NA[1]	0.0972
Gwqmn	Shallow Aquifer Water Depth	6	NA[1]	0.0639
Blai	Maximum Potential Leaf Area	7	NA[1]	0.0613
Revapmn	Threshold depth of water in the shallow aquifer for "revap" to occur (mm H2O)	8	NA[1]	0.0330
Canmx	Maximum canopy storage (mm H2O)	9	NA[1]	0.0317
Sol_K	Saturated hydraulic conductivity of first soil layer (mm/hr)	10	NA[1]	0.0296

Notes:
1. NA = Not Applicable, not used in either streamflow or sediment yield calibration

Model Calibration

Once the sensitive parameters were identified, calibration was performed. Calibration is typically accomplished by changing input parameters and determining what input parameters yield simulated outputs that match the observed data from the field. The Chorro Creek Watershed model was calibrated using SCE-UA to alter the five highest ranked sensitivity result parameters using observed streamflow data at Canet and sediment data from the *Paired Watershed Study*. After running the model calibration, the model can be used to determine approximation parameters, such as streamflow and sediment yield, at various locations in the watershed. After running calibration, the model is rerun with the optimized parameters from calibration to produce the most accurate model output. The optimal SWAT parameters identified during calibration were applied to all of the subwatersheds in the Chorro Creek Watershed to estimate sediment yield, which would have been produced from the entire watershed if no BMPs were installed.

Calibration data from the streamflow calibration task is shown in Figures 6.1 and 6.2. Figure 6.1 shows the relationship between the model simulation output and observed data for both the final calibration and validation phases of calibration. Figure 6.2 shows a detailed data set of the calibration phase.

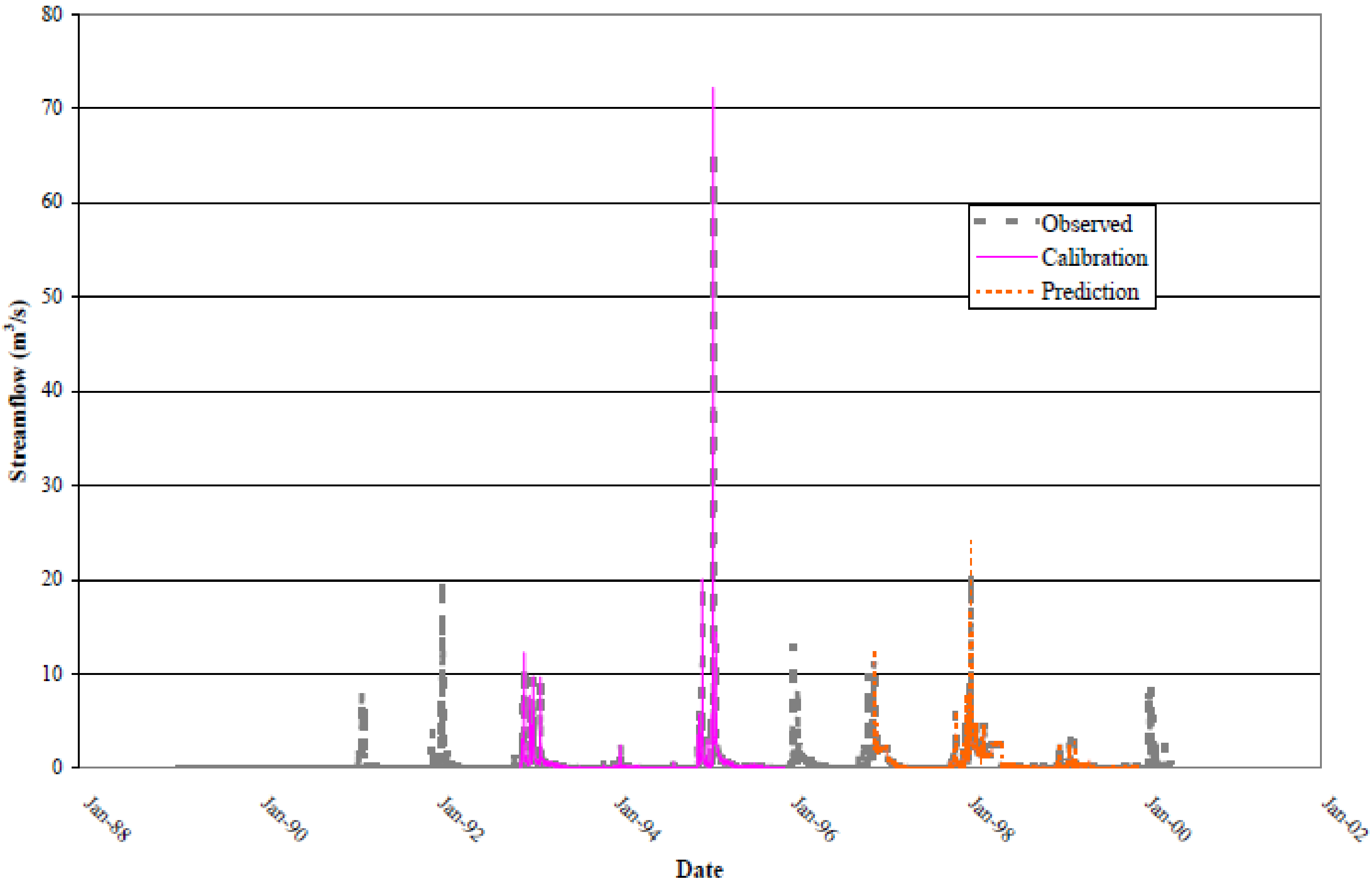

Figure 6.1: Comparison of Simulated and Observed Streamflow for Canet Road

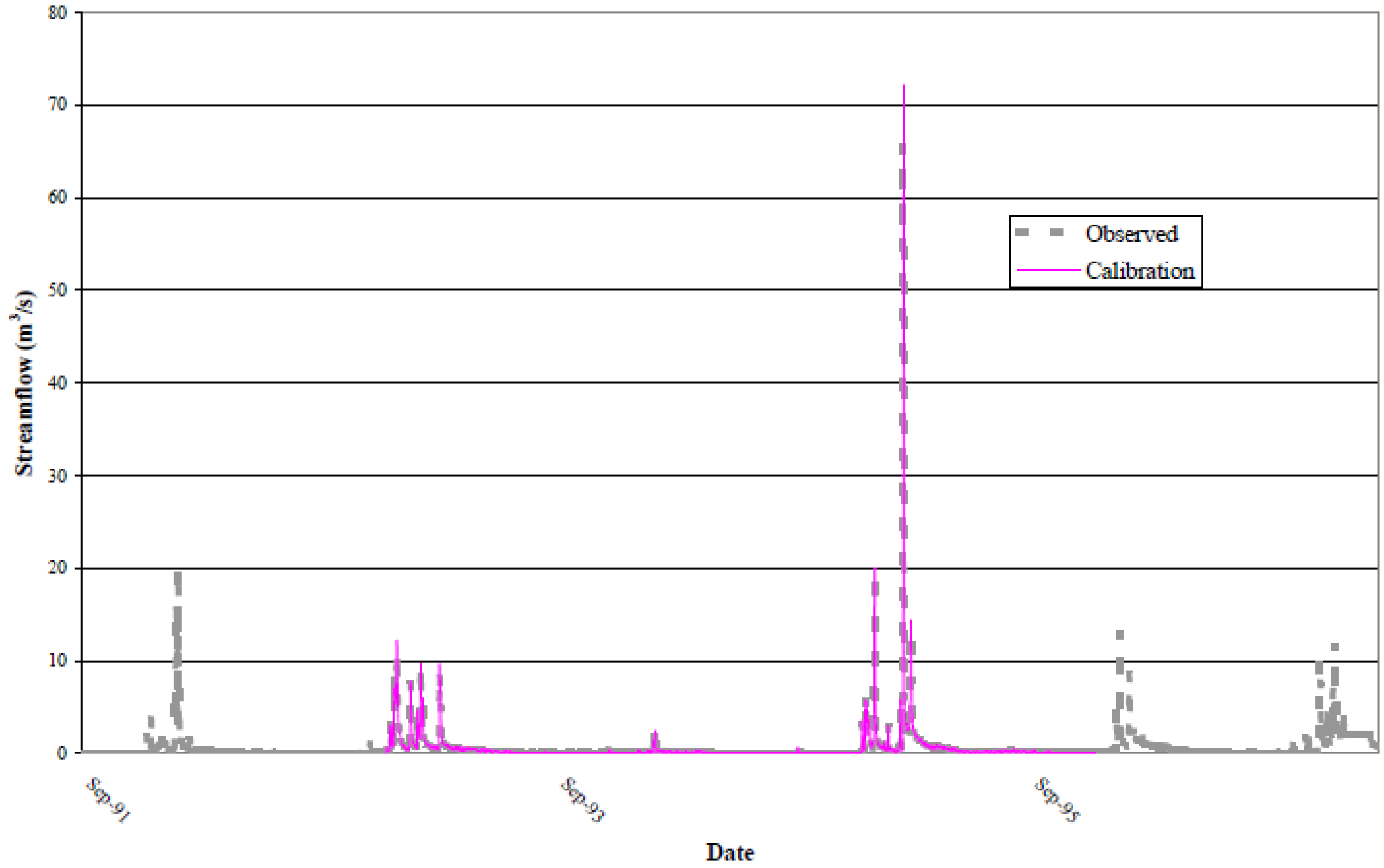

Figure 6.2: Calibration Period of Streamflow for Canet Road

Validation

The final calibration and validation simulation output closely trends the observed data at the Canet Road stream gage, meaning that the model is capable of accurately predicting streamflow in the Chorro Creek Subwatershed. This close correlation supports the application of the model as an accurate representation of streamflow, and demonstrates the model's ability to predict streamflow in response to the input weather data. Figure 6.3 shows the validation model run, and shows a close correlation between the observed and predicted data set. A streamflow calibration plot is shown in Figure 6.4 showing the relationship between the simulated output and observed data. The y = x line represents a perfect relationship between the two datasets. The data plots slightly above this reference line indicating that the model over-predicts streamflow slightly compared to the actual observed flow.

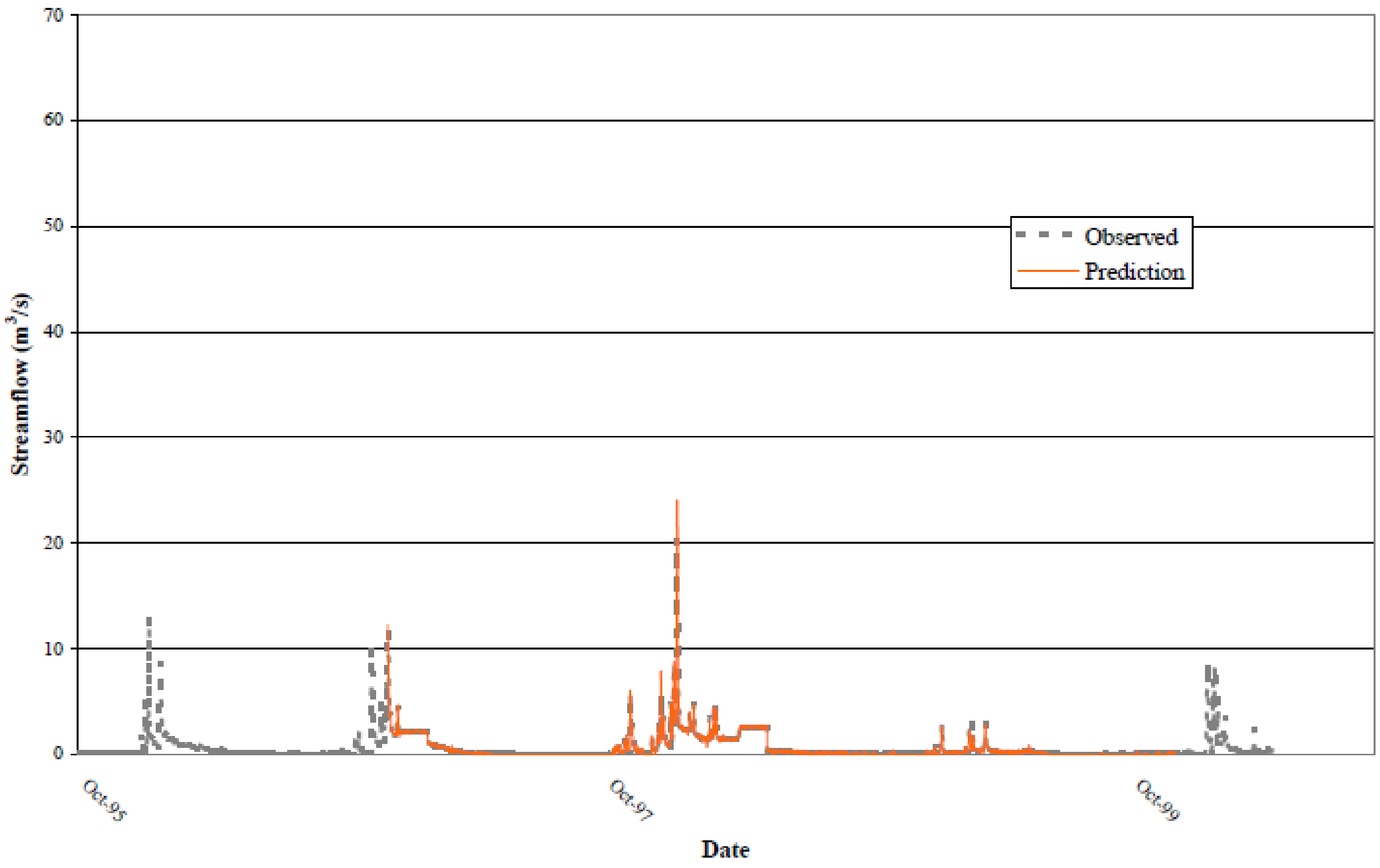

Figure 6.3: Validation of Streamflow for Canet Road

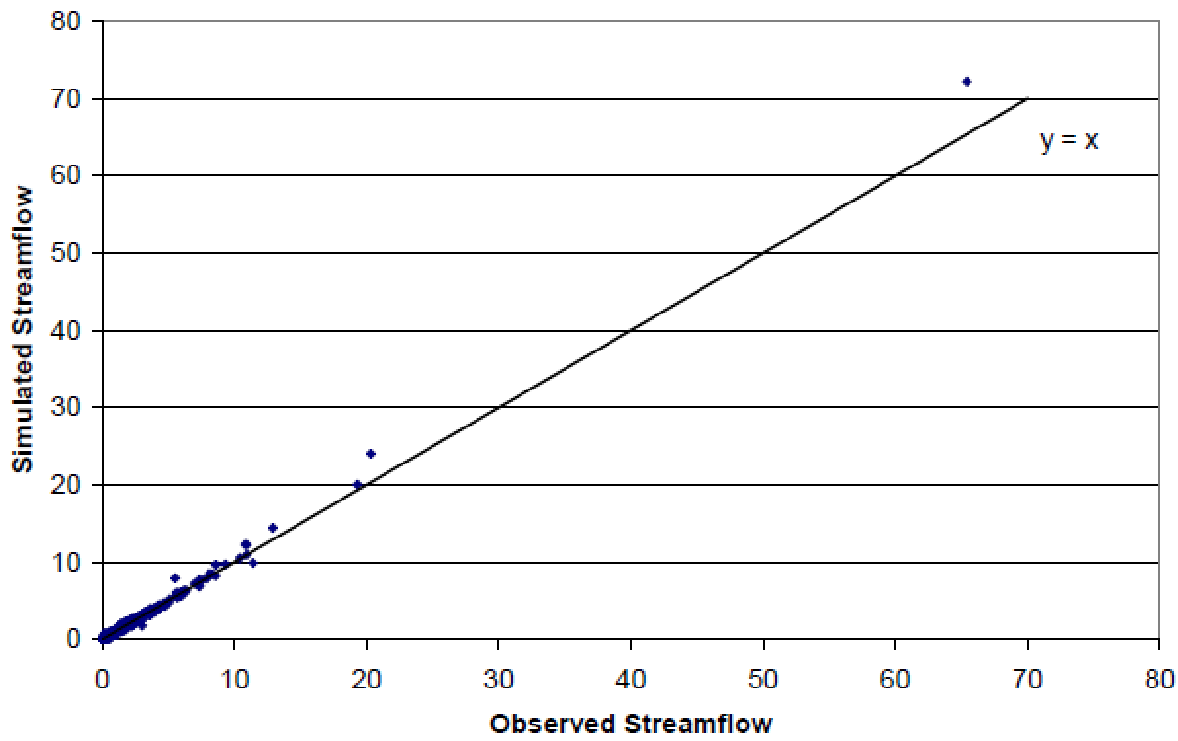

Figure 6.4: Streamflow Calibration Plot (Canet Road Gage)

The calibration for sediment yield in the basis was not as robust as the streamflow calibration. The *Paired Watershed Study* indicated that accurate measurement of sediment yield data in the basin was difficult to collect due to the large magnitude fluctuation in streamflow. SWAT was unable to sufficiently calibrate sediment yield in the basin within an industry standard acceptable error. It is suspected that the quality and frequency of existing sediment data in the basin is not sufficient to conduct accurate calibration of a sediment yield model. Due to this gap in necessary data, the accuracy of the model simulated sediment yield is not guaranteed to be a true representation of the actual quantitative sediment yield in the basin. An attempt to calibrate sediment yield using a single high flow event at the Chorro Flats Project location was used to establish a minimal model calibration for sediment yield. While quantitative sediment yield is currently outside the capabilities of the model, comparisons of pre and post BMP implementation can be made on a percent reduction basis by comparing the percent change in the *with* and *without* BMP modeling scenarios.

CHAPTER 7

RESULTS AND DISCUSSION

To estimate sediment yield from the watershed for the post-BMP implementation scenario, SWAT parameters, which were believed to be affected by the BMPs installed in the specific subwatershed, were modified using guidance by literature (Arabi, et al. 2007; Bracmort, et al. 2006). As the major BMPs were installed before 1998, the post-BMP scenario simulation was done for the 1998-2008 period. Annual average sediment yield values obtained for the *with* BMP and the *withou*t BMP scenarios were compared to evaluate the effectiveness of the BMPs. Sediment transport behavior of the stream channels in the lower part of the watershed are not calibrated in this study due to lack of data at lower reaches of the basin. Only stream flow calibration was performed for the lower portion of the watershed. In spite of this accuracy issue with regards to the sediment that gets to the mouth of the watershed where the Chorro Flats project is located, effectiveness of the Chorro Flats project was also evaluated based on sediment yield estimates obtained at the upstream and downstream ends of the project. To model the Chorro Flats project, the stream channel that passes through the project was modified to make it shallower and milder to allow overtopping of the main channel into the adjacent field where sediment should deposit. Slope of the subwatershed was also reduced to enable deposition of sediment in the flat. For cattle exclusion projects and channel stabilization projects, model parameters that simulate erodibility of the channel were modified along with land use.

Evaluation of Global Watershed BMPs

With flow calibration of the model complete, evaluation of sediment reduction BMPs in the watershed was able to be conducted. Characteristic parameters of each HRU and general model parameters were modified to reflect the implementation of four different BMPs. Modification of these parameters were based on previous research and modeling efforts conducted in watersheds with sufficient data for sediment loading calibration as presented in Arbi, et al. (2007) and Bracmort, et al. (2006). By implementing similar parameter manipulation the effect of each theoretical BMP was able to be measured against the no change or no implemented BMP scenario. The initial sediment yield of each of the 118 HRUs is shown in Figure 7.1.

Chorro Flats Project

For the Chorro Creek Watershed, average annual sediment yield obtained was 4.81 tons/ha and 5.20 tons/ha for the *with* and *without* BMP scenarios, respectively. This shows approximately an 8 percent reduction in sediment yield from the entire Chorro Creek watershed due to the BMPs implemented in Chumash Creek watershed(see Figure 7.2), the cattle exclusion project in Dairy Creek watershed, the cattle exclusion project downstream of Chorro reservoir and the grazing management project in the San Bernardo Creek Watershed. Improvement in sediment reduction achieved at the local subwatersheds where the BMPs are installed is as high as 50 percent. Most of these BMP projects have helped to reduce erodibility of the stream banks and could decrease sediment that leaves the subwatershed. This role was not factored into the 8 percent figure indicated here.

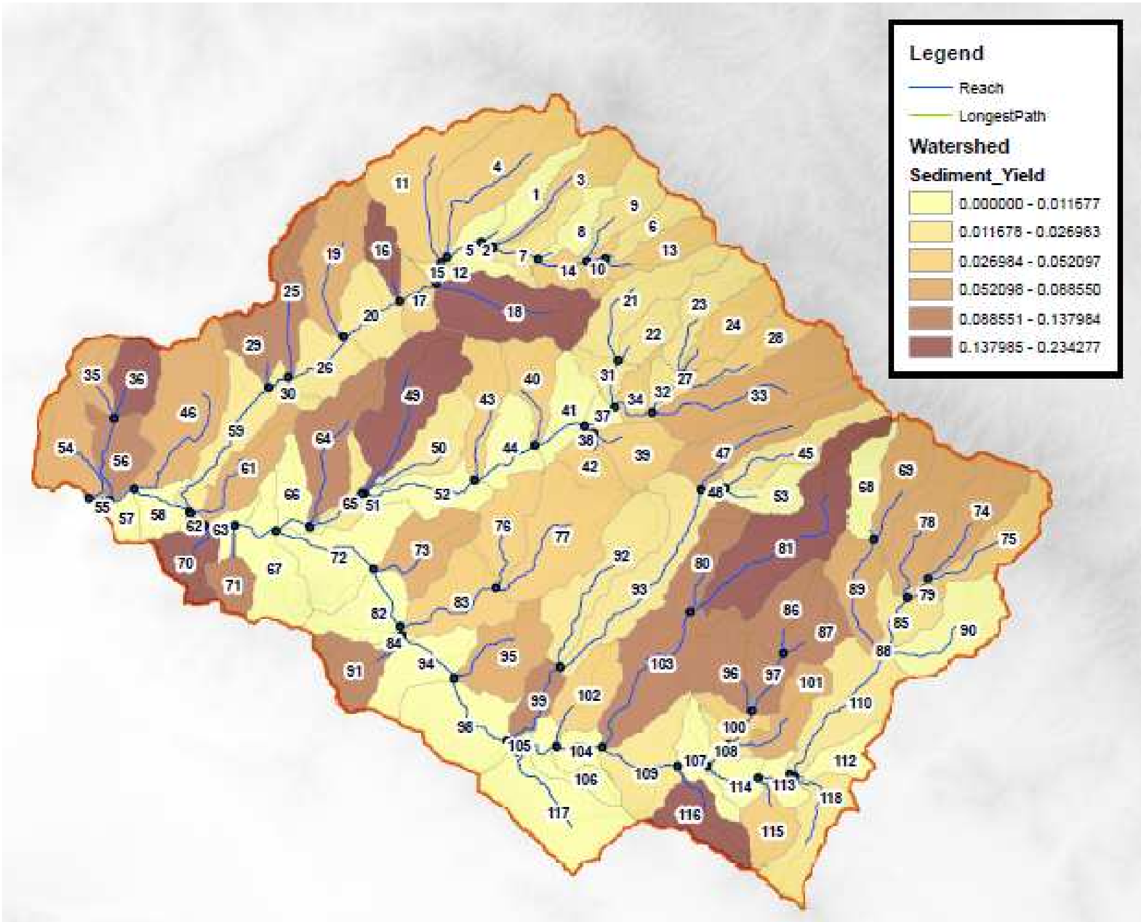

Figure 7.1: Chorro Watershed Sediment Yield (Ton/ha/year)

Figure 7.2: Chorro Flats Project Vicinity Map

Exclusion Fencing

Exclusion fencing is used to prevent livestock, such as cattle from accessing creek beds and slopes. When livestock migrate in and out of the riparian banks and creek beds, they loosen up soil, which can lead to increased erosion and soil available for sediment transport during high flow events. Actual BMP studies have found that exclusion fencing can reduce sediment loading, but results are influenced by a variety of local factors, including soil type, channel geometry, and level of livestock farming.

To estimate the effects of exclusion fencing implementation the channel erodibility factor (*CH_EROD*) was adjusted using the methodology presented in Arabi , et al. (2007).   The erodibility factor in SWAT is based on Wischmeier's and Smith's (1978) defined relationship of a soils susceptibility to erosion. Wischmeier and Smith determined that soils become less susceptible to erosion as the silt content of the soil decreases. They established and published a direct correlation between silt fraction and erodibility. SWAT uses a conceptually similar relationship to determine the soil erodibility factor for each soil type. Arabi, et al. (2007) determined that a reduction in the channel erodibility factor to 0.001 reflected a hardened channel that is not susceptible to any erosion.

Sediment reductions we observed and compared to the results established from the *Paired Watershed Study* on Chumash and Walters Creeks, located in the study watershed. Parameters were modified along two main tributaries in the basin where cattle exclusion fencing has been implemented in the basin shown in Figures 7.3 and 7.4. The *Paired Watershed Study* observed reductions in sediment loading of about 8-10 percent on an annual basis. The erodibility factor was adjusted to 0.2 to reflect the effects of limiting livestock access to the soil within the channel, in the Chorro Watershed Model to yield the same reduction for the localized area.

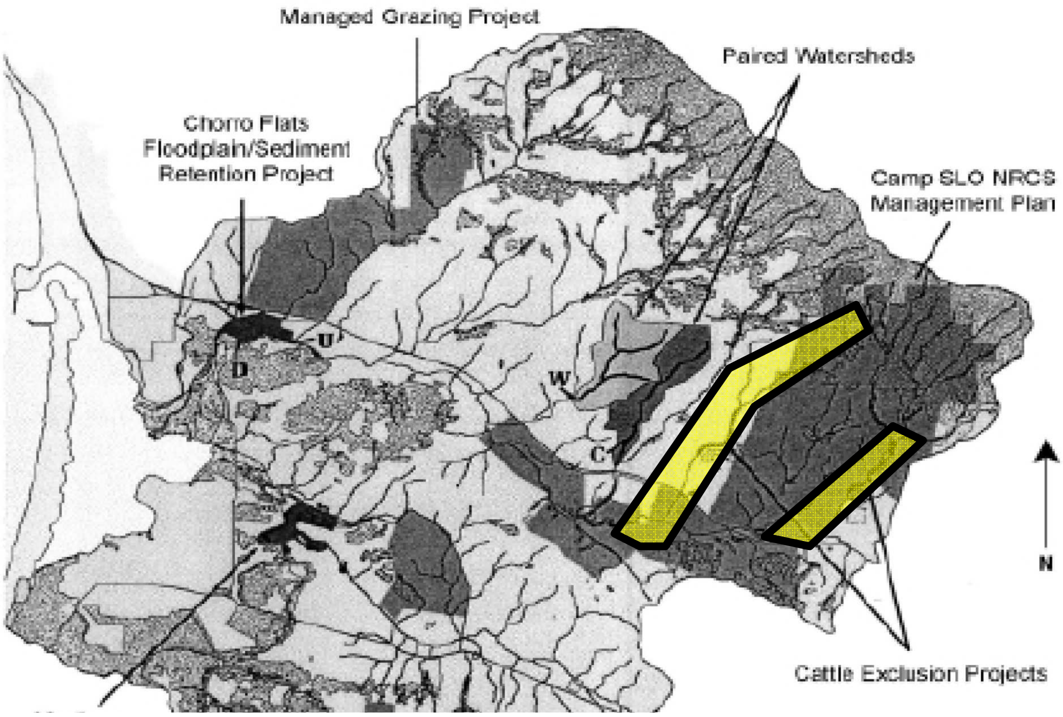

Figure 7.3: Exclusion Fencing in Chorro Creek Subwatershed (Source: CCRWQCB, 2003)

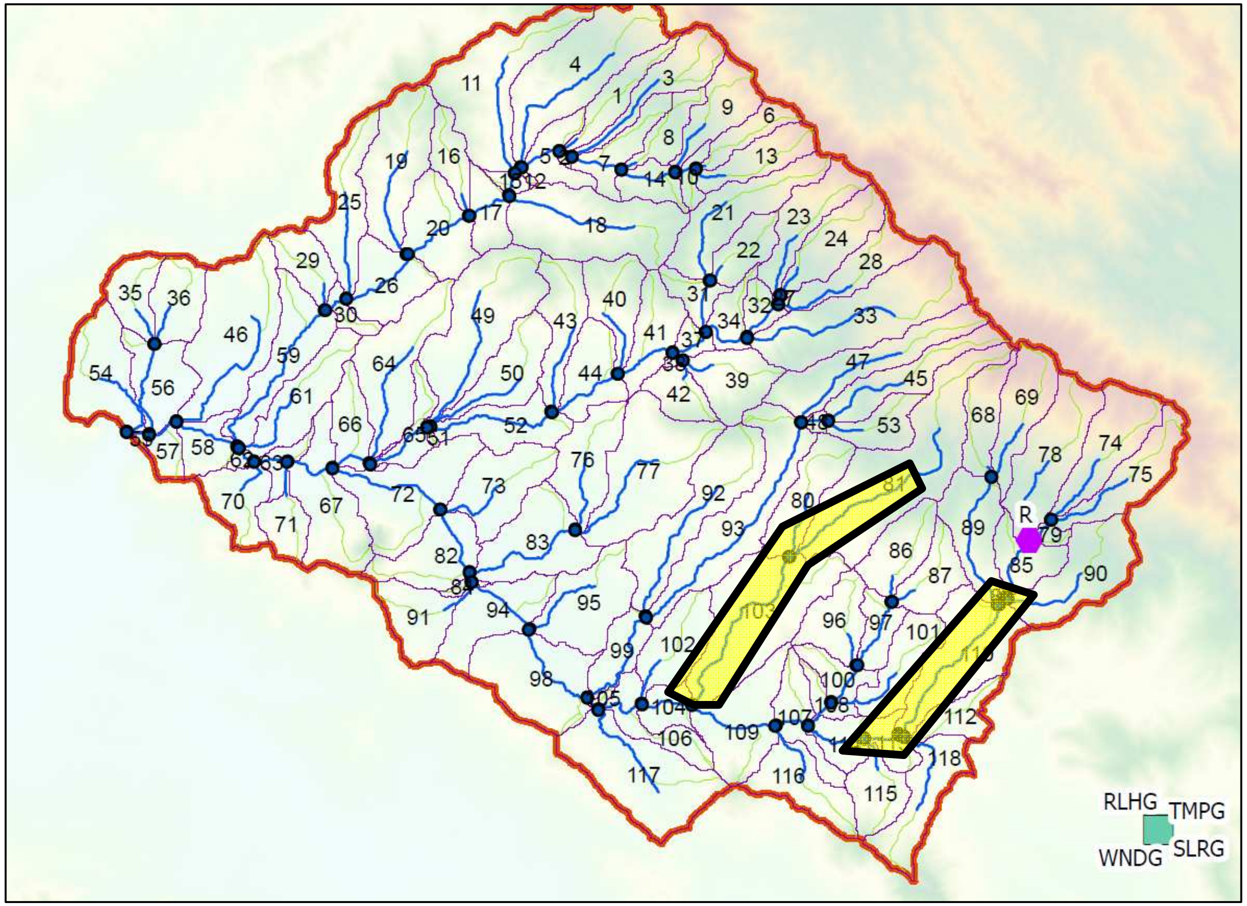

Figure 7.4: Location of Exclusion Fencing in SWAT Model

After calibrating the reduction in sediment loading, the model results for the entire Chorro Watershed were analyzed. This analysis was done by comparing the total annual sediment yield from the HRUs with more than 50 percent of its land use dedicated to livestock grazing between the *without* BMP and the *with* BMP scenarios. Annual reductions from the installation of exclusion fencing on grazed lands within the watershed resulted in a reduction of 4 percent to annual sediment yield. Other studies determined that exclusion fencing can reduce sediment loading of the implementation area by approximately 4-6 percent if the BMP is properly installed and maintained. The benefits of this BMP may not be directly additive with other implemented BMPs, such as stream bank stabilization, due to overlap of benefits. Figure 7.5 shows the output of the *with* and *without* BMP SWAT model scenarios for this BMP.

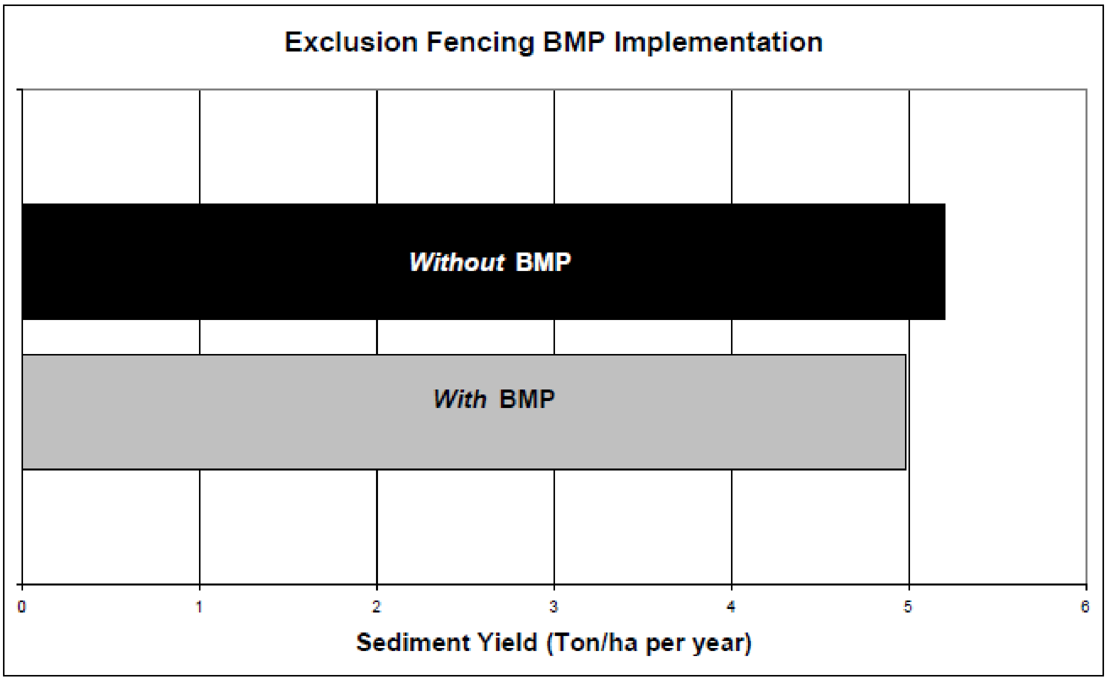

Figure 7.5: Results of Exclusion Fencing BMP Implementation

Sediment Harvesting

Sediment harvesting consists of addition or modification of wide and shallow sloped channels or overflow channels to trap and deposit sediment during high flow events. This BMP was analyzed through the case study of Chorro Flats described previously. The *Paired Watershed Study* determined that the Chorro Flats Sediment Capture Project has an operation life of approximately 30 years. Due to the large land requirements and reoccurring operation and maintenance activities required, implementation areas are limited. Simulation modeling of the implemented Chorro Flats Sediment Capture Project yielded high sediment load reductions. The SWAT model simulated sediment reductions of 8 percent. The Chorro Flats Final Report states that the project captured 23 percent of the sediment load that passed the project. Since only a portion of the creek flow passes through the designed overflow channel and into the Chorro Flats area the simulated 8 percent reduction in sediment loading to Morro Bay is consistent with the results of the Chorro Flats Report. Figure 7.6 shows the output of the *with* and *without* BMP SWAT model scenarios for this BMP.

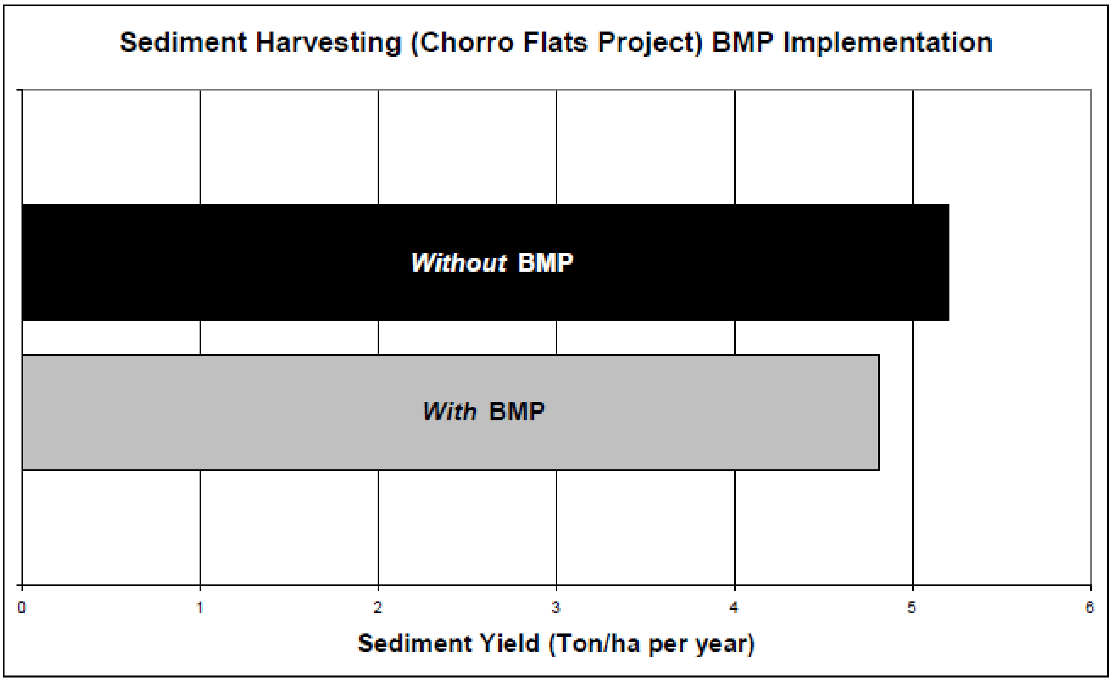

Figure 7.6: Results of Sediment Harvesting BMP Implementation

Stream Bank Stabilization

Stream bank stabilization utilizes erosion resistant materials such as vegetation, rock, and soil concrete mixtures to armor the banks of a creek bank of channel. The installed material stabilizes the soil on the banks of the channel and reduces soil erosion by limiting the amount of loose and exposed soil that is available for sediment transport downstream due to additional channel cover. There is debate over the impacts of artificial stream bank stabilization on riparian habitat, but this analysis focuses on the effectiveness of the implemented BMP at reducing sediment yield within the study subwatershed.

Implementation of stream bank stabilization was modeled using guidance from Arabi, et al. (2007). Arabi determined that Manning's n coefficient, channel geometry

(*CH_D* and *CH_W2*), and channel cover factor are the model parameters that should be modified to accurately model grassed water ways. The research suggests modifying the *CH_N2* value of 0.3 to 0.4.

By using this method both the change in the banks channel cover and the increase in channel friction are factored into the model. There was insufficient data in the watershed to determine the reduction in sediment yield from the implementation of stream bank stabilization alone, since it was implemented along with other BMPs throughout the watershed in field studies. Due to the limited data to calibrate the model for the *with* BMP scenario, care was taken to adjust the channel cover factor (*CH_COV*) and Manning's n coefficient for the channel. The channel cover factor was modified to 0.001 to reflect an arbitrary low non-zero value. This methodology is consistent with the adjustment suggested by Arabi 2004 for grassed waterways. The Manning's coefficient was modified in HRUs whose existing Manning's n was 0.025 or lower, signifying there was little or no vegetation or hardscape on stream banks. The CH_N2 was manually overridden to 0.065 to reflect a typical value for a channel after the implementation of stream bank stabilization efforts.

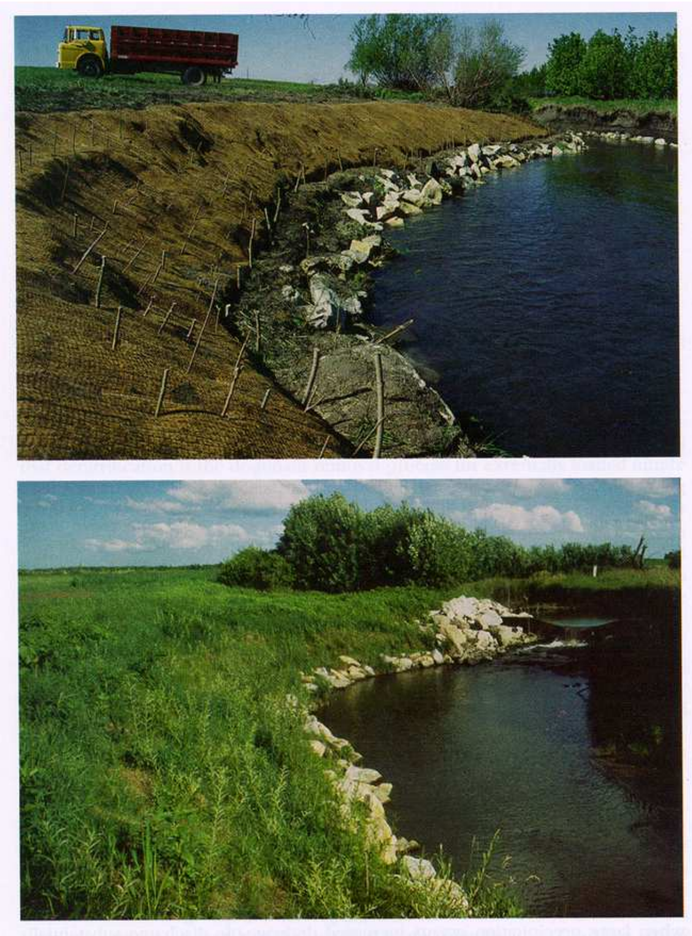

Figure 7.7: Examples of Stream Bank Stabilization (Source: Iowa State University)

After adjusting the Manning's n coefficient and channel cover factor, the model simulation yielded a 6 percent reduction in annual sediment yield compared to the *without* BMP scenario. Figure 7.8 shows the output of the *with* and *without* BMP SWAT model scenarios for this BMP.

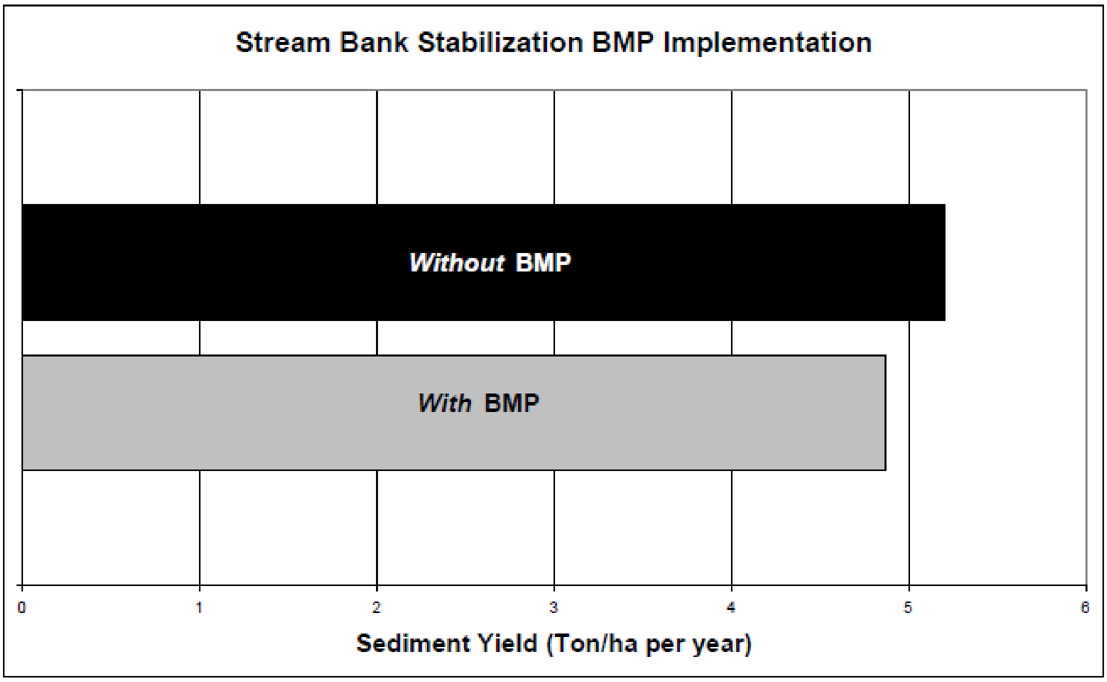

Figure 7.8: Results of Sediment Harvesting BMP Implementation

Conservation Crop Rotation

The crop rotation module within SWAT was used to set up a crop rotation schedule including periods of peas, alfalfa , lettuce, and three month crop fallow period, when harvesting is temporarily suspended. This period of crop fallowing reduces sediment yield due to reductions in erosion. This BMP resulted in a reduction of annual sediment yield of approximately 4 percent. Figure 7.9 shows the output of the *with* and *without* BMP SWAT model scenarios for this BMP.

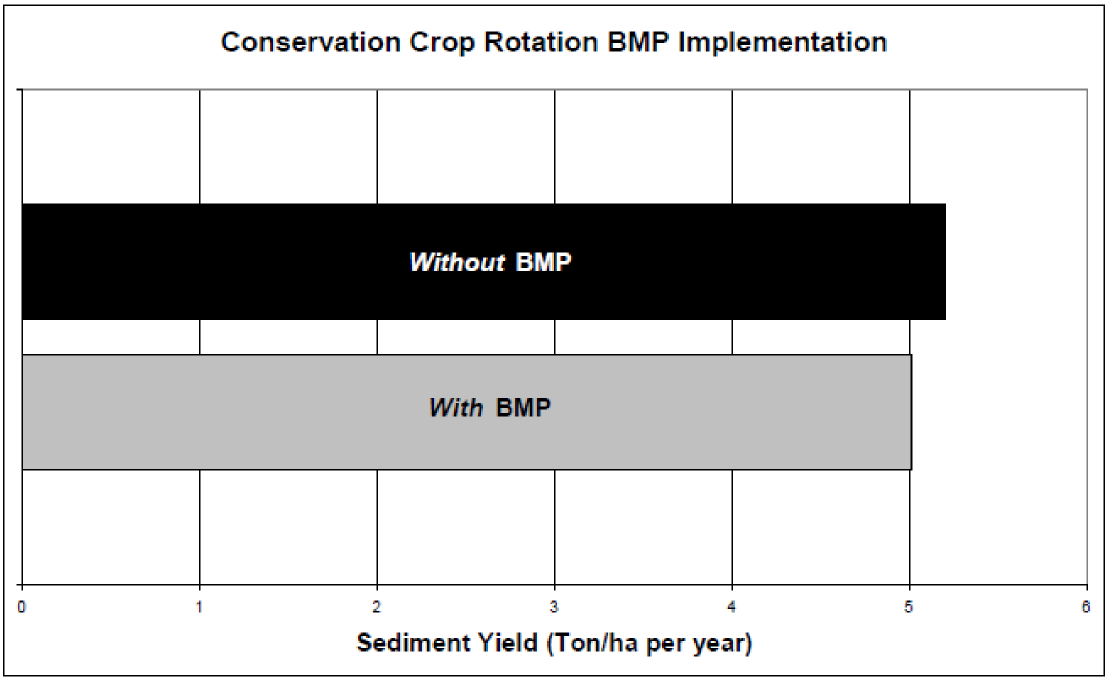

Figure 7.9: Results of Crop Rotation BMP Implementation

CHAPTER 8

CONCLUSION

Although additional information is needed to conclusively determine the effectiveness of BMP implementation, SWAT can be used to predict a combination of BMPs and locations that will be most effective in the watershed. While the accurate quantities of sediment transport prevention can not be determined with the data that is currently available, the model can be used to screen BMPs options and provide guidance on relative effectiveness of the various BMPs.

Table 8.1: Chorro Creek Subwatershed BMP Effectiveness Ranking

Rank	Best Management Practice	Sediment Reduction
1	Sediment Harvesting	8%
2	Stream Bank Stabilization	6%
3	Exclusion Fencing	4%
4	Crop Rotation	4%

Through the development of this work, it was discovered that additional data in the Chorro Creek Watershed is needed to develop a broader dataset before detailed conclusions can be drawn from any modeling effort. The most critical data to collect to evaluate watershed management strategies is sediment data and rainfall data in the watershed during high flow events. The various organizations and agencies focused on the sediment issues in the basin should collectively focus resources on gathering quality sediment and rainfall data in the watershed to both predict future BMP implementation impacts and monitor the impacts of existing BMPs.

As more data becomes available and watershed managers become more familiar with GIS and spatially distributed models, tools like SWAT will become more widely used in the planning and implementation stages of BMP implementation. Having organized data libraries to bring together robust watershed models adds great value to future work and studies. While quality sediment data is not currently available in the watershed, robust sediment data may become available in the future. Computer simulation models, such as this SWAT model, can be use with quality sediment data and continuous high flow sediment loading monitoring to track sediment behavior in the Chorro Creek Subwatershed. This data is easily added to the existing model through sediment loading calibration. With this data a wider application of the model would provide great benefit to BMP implementation projects and determine the potential benefits of these efforts within the basin.

This evaluation consolidates the information from the various BMPs that have been implemented in the watershed into a global sediment model approach. The implemented BMPs were modeled using a geospatially distributed computer model that allows for the input of a wide variety of input parameters. The BMP evaluation can benefit greatly from the increasing amount of available Geographical Information System (GIS) data. The two goals of this evaluation were to organize and document the various sources of data and analysis that have been performed to date in the Chorro Creek Subwatershed and to present a global evaluation of the effectiveness of the BMPs that have been implemented in this watershed using SWAT in order to simulate the pre- and post-BMP implementation characteristics evaluated in the Chorro Creek Subwatershed. Combining the data and efforts of past BMP evaluations, land use, soil type, rainfall, and streamflow data, past statistical evaluations, and model sensitivity analysis helped build and calibrate a robust SWAT model. This model can be used to track BMP evaluation efforts, as well as other watershed management tasks. Through the evaluation of BMPs in the Morro Bay Watershed, efforts can be made to implement the more successful BMPs in the watershed. SWAT can be used as a prediction model to estimate the effectiveness of BMP implementation and aid in the selection of appropriate BMPs for the specific watershed.

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APPENDIX A

Input Parameter Tables

Table 4.1: Initial Model Parameters

SUBBASIN	SUBBASIN AREA (Hectare)	LANDUSE	SOIL CLASSIFICATION	CN2
1	67.2	RNGB	CA014	92.5
2	4.2	RNGB	CA526	100
3	98.8	RNGE	CA014	98.75
4	235.9	RNGE	CA014	98.75
5	59.7	RNGB	CA506	92.5
6	51.9	RNGB	CA014	92.5
7	70.1	RNGB	CA014	92.5
8	52.9	RNGB	CA014	92.5
9	90.4	RNGB	CA014	92.5
10	22.9	RNGB	CA014	92.5
11	221.3	RNGB	CA506	92.5
12	3.7	RNGB	CA506	92.5
13	80.2	RNGE	CA014	98.75
14	47.0	RNGB	CA526	100
15	14.2	RNGB	CA506	92.5
16	56.5	RNGE	CA526	100
17	57.1	RNGB	CA201	92.5
18	228.8	RNGB	CA526	100
19	164.8	RNGE	CA506	94
20	115.3	RNGB	CA201	92.5
21	147.7	RNGB	CA014	92.5
22	62.5	RNGB	CA014	92.5
23	104.9	RNGB	CA014	92.5
24	103.0	RNGE	CA014	98.75
25	122.6	RNGE	CA203	100
26	101.2	RNGE	CA201	98.75
27	2.6	RNGE	CA526	105
28	91.7	RNGE	CA014	98.75
29	63.2	RNGE	CA201	98.75
30	24.5	RNGE	CA591	98.75
31	41.8	RNGE	CA503	86.25
32	32.2	RNGE	CA001	86.25
33	261.5	RNGE	CA014	98.75
34	46.1	RNGB	CA203	100
35	68.6	RNGE	CA203	100
36	83.8	RNGE	CA201	98.75
37	21.1	RNGB	CA511	92.5
38	4.2	RNGB	CA201	92.5
39	97.1	RNGB	CA201	92.5
40	91.7	RNGB	CA201	92.5
41	88.2	RNGB	CA147	100
42	54.9	RNGB	CA201	92.5

SUBBASIN	SUBBASIN AREA (Hectare)	LANDUSE	SOIL CLASSIFICATION	CN2
43	100.8	RNGB	CA201	92.5
44	92.8	RNGB	CA201	92.5
45	106.2	RNGB	CA014	92.5
46	243.5	RNGE	CA203	100
47	151.1	RNGE	CA014	98.75
48	8.7	RNGE	CA605	86.25
49	227.1	RNGE	CA201	98.75
50	105.2	RNGB	CA201	92.5
51	3.0	RNGE	CA147	100
52	97.7	RNGB	CA203	100
53	64.9	RNGB	CA513	48.75
54	137.0	RNGE	CA203	100
55	4.3	WETN	CA243	98.75
56	99.4	RNGE	CA203	100
57	33.3	RNGE	CA147	100
58	56.6	RNGE	CA147	100
59	133.7	RNGE	CA203	100
60	0.4	RNGE	CA147	100
61	114.9	RNGE	CA203	100
62	8.3	RNGE	CA147	100
63	29.1	AGRR	CA511	100
64	171.5	RNGE	CA203	100
65	48.8	RNGE	CA511	98.75
66	71.1	RNGE	CA203	100
67	153.7	RNGE	CA201	98.75
68	76.1	RNGE	CA001	86.25
69	110.7	RNGE	CA014	98.75
70	84.2	RNGE	CA201	98.75
71	56.1	RNGE	CA201	98.75
72	180.9	RNGE	CA201	98.75
73	127.3	RNGE	CA203	100
74	130.3	RNGE	CA014	98.75
75	112.7	RNGE	CA014	98.75
76	116.0	RNGB	CA201	92.5
77	233.1	RNGB	CA201	92.5
78	163.4	RNGE	CA014	98.75
79	15.5	RNGB	CA001	76.25
80	103.3	RNGE	CA203	100
81	321.0	RNGE	CA201	98.75
82	111.5	RNGE	CA201	98.75
83	152.9	RNGB	CA240	100
84	8.6	WETN	CA240	100
85	69.3	RNGE	CA001	86.25
86	90.6	RNGE	CA201	98.75

SUBBASIN	SUBBASIN AREA (Hectare)	LANDUSE	SOIL CLASSIFICATION	CN2
87	73.3	RNGE	CA201	98.75
88	3.0	RNGB	CA002	76.25
89	114.9	RNGE	CA506	98.75
90	153.0	RNGE	CA001	86.25
91	92.9	RNGE	CA203	100
92	189.5	RNGB	CA201	88
93	215.5	RNGB	CA201	92.5
94	121.2	RNGE	CA203	100
95	140.6	RNGE	CA203	100
96	85.8	RNGE	CA201	98.75
97	52.1	RNGE	CA201	98.75
98	185.8	RNGE	CA605	86.25
99	61.5	AGRR	CA511	100
100	47.4	RNGE	CA147	100
101	94.7	RNGE	CA203	100
102	101.6	RNGE	CA201	98.75
103	258.6	RNGE	CA201	94
104	44.1	URLD	CA240	98.75
105	6.4	AGRR	CA511	100
106	70.0	URLD	CA240	98.75
107	70.7	RNGE	CA147	100
108	26.3	RNGE	CA147	100
109	146.3	RNGE	CA201	98.75
110	182.0	RNGE	CA201	98.75
111	0.4	URLD	CA511	90
112	58.6	RNGE	CA335	86.25
113	38.9	URLD	CA511	90
114	51.9	URLD	CA511	90
115	76.3	RNGE	CA147	100
116	106.7	RNGE	CA201	98.75
117	224.1	RNGE	CA605	86.25
118	121.5	RNGE	CA147	95

Table 4.2: Additional Model HRU Parameters

Variable Name	Definition
HRU	Hydrologic response unit number
GIS	GIS code reprinted from watershed configuration file (.fig). See explanation of subbasin command (Chapter 2).
SUB	Topographically-defined subbasin to which the HRU belongs.
MON	Daily time step: the julian date, Monthly time step: the month (1-12), Annual time step: 4-digit year, Average annual summary lines: number of years averaged together
AREA	Drainage area of the HRU (km2).
PRECIP	Total amount of precipitation falling on the HRU during time step (mm H2O).
IRR	Irrigation (mm H2O). Amount of irrigation water applied to HRU during the time step.
PET	Potential evapotranspiration (mm H2O). Potential evapotranspiration from the HRU during the time step.
ET	Actual evapotranspiration (soil evaporation and plant transpiration) from the HRU during the time step (mm H2O).
SW_INIT	Soil water content (mm H2O). For daily output, this column provides the amount of water in soil profile at beginning of day. For monthly and annual output, this is the average soil water content for the time period. The amount of water in the soil profile
SW_END	Soil water content (mm H2O). Amount of water in the soil profile at the end of the time period (day, month or year).
PERC	Water that percolates past the root zone during the time step (mm H2O). There is usually a lag between the time the water leaves the bottom of the root zone and reaches the shallow aquifer. Over a long period of time, this variable should equal groundwater
GW_RCHG	Recharge entering aquifers during time step (total amount of water entering shallow and deep aquifers during time step) (mm H2O).
DA_RCHG	Deep aquifer recharge (mm H2O). The amount of water from the root zone that recharges the deep aquifer during the time step. (shallow aquifer recharge = GW_RCHG - DA_RCHG)
REVAP	Water in the shallow aquifer returning to the root zone in response to a moisture deficit during the time step (mm H2O). The variable also includes water uptake directly from the shallow aquifer by deep tree and shrub roots.
SA_IRR	Irrigation from shallow aquifer (mm H2O). Amount of water removed from the shallow aquifer for irrigation during the time step.
DA_IRR	Irrigation from deep aquifer (mm H2O). Amount of water removed from the deep aquifer for irrigation during the time step.
SA_ST	Shallow aquifer storage (mm H2O). Amount of water in the shallow aquifer at the end of the time period.
DA_ST	Deep aquifer storage (mm H2O). Amount of water in the deep aquifer at the end of the time period.
SURQ_GEN	Surface runoff generated in HRU during time step (mm H2O).

Variable Name	Definition
SURQ_CNT	Surface runoff contribution to streamflow in the main channel during time step (mm H2O).
TLOSS	Transmission losses (mm H2O). Water lost from tributary channels in the HRU via transmission through the bed. This water becomes recharge for the shallow aquifer during the time step. Net surface runoff contribution to the main channel streamflow is calculated for each time step.
LATQ	Lateral flow contribution to streamflow (mm H2O). Water flowing laterally within the soil profile that enters the main channel during time step.
GW_Q	Groundwater contribution to streamflow (mm H2O). Water from the shallow aquifer that enters the main channel during the time step. Groundwater flow is also referred to as baseflow.
WYLD	Water yield (mm H2O). Total amount of water leaving the HRU and entering main channel during the time step. (WYLD = SURQ + LATQ + GWQ – TLOSS – pond abstractions)
DAILYCN	Average curve number for time period. The curve number adjusted for soil moisture content.
TMP_AV	Average daily air temperature (°C). Average of mean daily air temperature for time period.
TMP_MX	Average maximum air temperature (°C). Average of maximum daily air temperatures for time period.
TMP_MN	Average minimum air temperature (°C). Average of minimum daily air temperatures for time period.
SOL_TMP	Soil temperature (°C). Average soil temperature of first soil layer for time period.
SOLAR	Average daily solar radiation (MJ/m2). Average of daily solar radiation values for time period.
SYLD	Sediment yield (metric tons/ha). Sediment from the HRU that is transported into the main channel during the time step.
USLE	Soil loss during the time step calculated with the USLE equation (metric tons/ha). This value is reported for comparison purposes only.
W_STRS	Water stress days during the time step (days).
TMP_STRS	Temperature stress days during the time step (days).
LAI	Leaf area index at the end of the time period.
YLD	Harvested yield (metric tons/ha). The model partitions yield from the total biomass on a daily basis (and reports it). However, the actual yield is not known until it is harvested. The harvested yield is reported as dry weight.

Notes:
1. Source: SWAT 2005 Theory Documentation